

SUMMARY OF HEAVY ION THEORY

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ABSTRACT

Can we study hot QCD using nuclear collisions? Can we learn about metallic hydrogen from the impact of comet Shoemaker-Levy 9 on Jupiter? The answer to both questions may surprise you! I summarize progress in relativistic heavy ion theory reported at DPF '94 in the parallel sessions.

Lattice simulations of QCD demonstrate that matter at temperatures exceeding $T_c \sim 150$ MeV is very different from matter composed of hadrons.¹ Simulations commonly display dramatic changes in thermodynamic quantities, such as the energy density, in a narrow interval $|T - T_c| \lesssim 5$ MeV, indicating an abrupt transformation from hadronic to quark-gluon degrees of freedom. The underlying aim of the theoretical speakers in the heavy ion sessions has been to understand how properties of high temperature matter can be deduced from collisions of nuclei at RHIC and LHC at $\sqrt{s} = 200$ and 5500 GeV per nucleon, respectively. Is the high temperature state deconfined? Is chiral symmetry restored? Is the expected abrupt transformation a true phase transition? Physics demands *experimental* answers to these questions.

Talks in this session addressed the global dynamics of heavy ion collisions as well as specific probes of the high temperature state. The significant progress in understanding the collision dynamics at the Brookhaven AGS, $\sqrt{s} \sim 5$ AGeV, and the CERN SPS, $\sqrt{s} \sim 20$ AGeV was surveyed by Schlagel and Vogt. Sarcevic and Shuryak discussed two important probes of the dynamics that will be more important at higher energies: open charm and direct photon production. The suppression of J/ψ production in ion-ion collisions probes the deconfinement of the high temperature state. This topic was presented by Satz and Thews. Ayala and Petrides discussed the modification of parton distributions in nuclei, a related topic. Schäfer and Shuryak discussed the nature of the chiral transition. Disoriented Chiral Condensates, a possible probe of the dynamics of chiral symmetry breaking at RHIC and LHC, was discussed by Kluger.

What can we learn about high temperature QCD from nuclear collisions²? An analogous, similarly-complex question is, what can the impact of a comet with Jupiter teach us about the equation of state of hydrogen? We have all seen exciting images of the collisions of the fragments of the comet Shoemaker-Levy 9 with Jupiter that took place

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from 16 to 22 July, 1994. Observations of the impacts are providing new information on comet structure and the stratification and composition of Jupiter's atmosphere.³ Indeed, the speed of sound in metallic hydrogen⁴ can be measured if reflections of downward-launched acoustic waves from Jupiter's core can be observed.⁵

1. Collision Dynamics

A very important issue in the AGS and SPS fixed-target experiments has been the *stopping power*. The extent to which the projectile ion is stopped ('slowed' is more accurate) as it crashes through the target nucleus depends on how the constituents interact. Should one treat the constituents as nucleons or quarks on the time scales of the collision? Is resonance formation important in the nucleon rescattering? Is there a formation time for secondary particle production?

Data on stopping comes primarily from the rapidity distribution of protons. Schlagel showed that the AGS proton data for projectiles as large as Au can be described by a purely hadronic rescattering model that incorporates resonance formation. He also showed that the omission of resonance formation does not describe the data. We expect formation time effects to become more important at the higher SPS energy. Vogt showed that SPS data for light projectiles can be described by string models that incorporate these effects. She argued that the Pb beam runs commencing this fall will be useful in deciding between string and hydrodynamic models.

In the case of Shoemaker-Levy 9, one is also interested in how the comet is stopped by Jupiter's atmosphere. The comet's structure determines the depth to which the comet penetrates. Stopping therefore provides information on comet structure. High temperature H_2O emission lines that are likely from the comet remnants have been observed.⁶ In the following table, I list aspects of the dynamics in nuclear collisions discussed at this meeting together with their analogs in the comet-Jupiter impact.

	Ion + Ion	Comet + Jupiter
stopping	baryon distribution proton dN/dy	comet remnants H_2O
thermalization	$\gamma, e^+e^-, \mu^+\mu^-;$ π, K, \dots, D	emission lines H_2S, CH_4
flow	directed flow ⁷	plume, ejecta
density	$J/\psi, \psi', \Upsilon$	absorption lines
EOS	DCC	seismic waves

Another central question in AGS/SPS nuclear collisions is *thermalization*: how effectively is the momentum of the projectile distributed among the participant nucleons and produced hadrons? Do these hadrons reach local thermal equilibrium and undergo collective flow? The abundance of produced particles such as pions, kaons and antiprotons indicates the extent to which particles interact and thermalize. Shuryak observed that photon and dilepton production can be used to measure the temperatures that the system achieves, although backgrounds can be formidable in practice. In the comet-Jupiter collision, the excitation of high temperature emission lines provide information on energy deposition. The observation of hot H_2S indicates that the

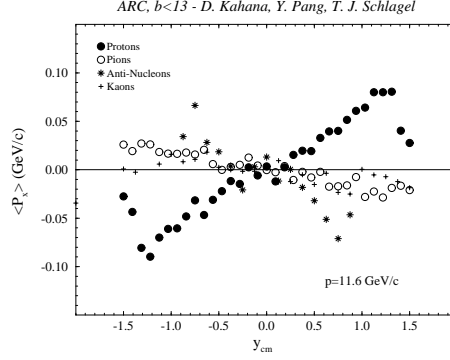


Fig. 1. Directed flow for various particle species in Au+Au at the AGS from Ref. [7]

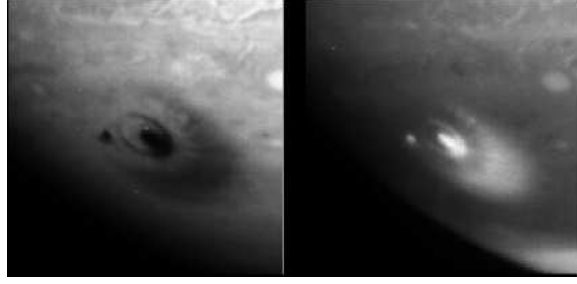


Fig. 2. Directed flow on Jupiter due to the impact of comet fragment G from the Hubble Space Telescope, Ref [8]. Left and right images are taken with green and methane filters respectively.

comet penetrated below Jupiter's ammonia-rich cloud cover into a layer containing ammonium hydrosulfide.³

Collective flow is another proposed indirect indication of thermalization. The directed flow of primary and produced particles in nuclear collisions can be deduced from exclusive measurements.⁷ The flow shown in Fig. 1 depends on particle type. For example, antiproton flow is anticorrelated with the proton flow because \bar{p} 's can annihilate with p 's. Observe that directed flow at the high AGS/SPS energies has little to do with the equation of state, EOS, since the eikonal approximation holds. Flow about the impact site of fragment G on Jupiter is shown in Fig. 2. The ejecta are asymmetrically distributed along the direction the impact and rich in CH_4 , indicating that the matter is from Jupiter. Note that in both cases the flow comes about because the collisions are not central.

New dynamical questions emerge at the higher RHIC and LHC energies. Minijets with transverse momenta larger than $p_T \sim 2$ GeV can produce perhaps up to 50% of particle production in Au+Au at RHIC. The low-x rise in the parton distributions measured at HERA implies that minijets can dominate particle production at LHC.⁹ Minijets can produce a high density of partons at short times $\sim p_T^{-1} \sim 0.1$ fm. These

partons can rescatter and thermalize forming what Shuryak calls ‘hot glue.’

Open charm production can serve as a measure of the temperature of this hot glue.¹⁰ The point is that charm is heavy and hard to make unless temperatures are very high. Most of the charm production is therefore expected to occur via primary hard perturbative scattering. However, semihard $gg \rightarrow c\bar{c}$ rescattering in a hot glue system can enhance charm production relative to perturbative expectations. Sarcevic pointed out that reliable perturbative estimates are needed to provide a benchmark and presented calculations to $O(\alpha_s^3)$.

2. J/ψ Suppression

J/ψ production provides a probe of the densities achieved in nuclear collisions that is also sensitive to deconfinement. Matsui and Satz observed that a J/ψ can exist in a low density quark gluon plasma as a QCD Bohr atom. However, color screening inhibits the binding of the $c\bar{c}$ pair when the temperature T is high enough that the screening length $\propto T^{-1}$ is smaller than the $c\bar{c}$ ’s Bohr radius. The c and \bar{c} can then wander apart to form open charm, leading to a suppression of the $J/\psi \rightarrow \mu^+\mu^-$ peak relative to the dimuon continuum.

A celestial analogy to J/ψ suppression is the modification of the intensity of hydrogen absorption lines in stars. The degree of ionization of hydrogen in the solar plasma depends on its temperature, *i.e.* a hotter star has fewer H atoms and more ions than a cool one. Correspondingly, the intensities of H absorption lines are reduced relative to the continuum in hot stars. Many processes contribute to the line spectra, so that detailed models are needed extract the temperature from the line intensity.¹¹ Nevertheless, line intensities are now a well established method for measuring stellar temperatures.

J/ψ suppression holds similar promise as a density probe in nuclear collisions, although its analysis is clearly much more complicated. While the production of the $c\bar{c}$ pair is perturbative and calculable, the formation of the bound state is not. Correspondingly, J/ψ production is not well understood even in $p\bar{p}$ collisions at the Tevatron (although there has been recent progress at high p_T ¹²). Thews presented a quantum mechanical analysis of the spacetime evolution of the $c\bar{c} \rightarrow J/\psi$. Such an analysis is necessary for understanding the formation of bound states in the high density environment.

In addition to the Matsui-Satz effect, there are several “background” contributions to J/ψ suppression. Although they are interesting manifestations of QCD, these contributions make the interpretation of density signals ambiguous. Initial state parton scattering broadens the p_T distributions in $pA \rightarrow J/\psi + X$ and Drell Yan, and is more-or-less understood.¹³ Ayala, Petridis and Sarcevic discussed the modification of parton distributions in nuclei compared to free nucleons. The resulting EMC and parton-shadowing effects alter J/ψ production, as Petridis emphasized. Final state scattering adds to the suppression effect, as hadronic reactions like $N + J/\psi \rightarrow D\bar{D}N$ and $\rho + J/\psi \rightarrow D\bar{D}$ can take place; see the presentations by Satz and Vogt.

A new direction taken at this meeting has been to seek *first-principles* constraints on models of the background contributions. Ayala reported on work with McLerran, Venugopalan and Jalilian-Marian on the development of new theoretical tools for cal-

culating parton distributions in large nuclei. Their idea is that at small x , the QCD scale is determined by the number of partons per unit transverse area, which varies as $A^{1/3}$. For very large nuclei, they formulate a weak-coupling semiclassical method to calculate the parton distributions. When perfected, these methods can provide important constraints on models of parton shadowing.

Satz presented work with Kharzeev in which they argue that the total J/ψ -nucleon cross section can be calculated. Following Peskin and Bhanot, they treated the heavy $c\bar{c}$ system as nearly pointlike and applied a short-distance operator-product-expansion analysis. In principle, cross sections calculated by this method can be used to constrain models of final state interactions. Of course, the fact that roughly half of hadroproduced J/ψ come from electromagnetic decays of relatively large χ states implies that not all of the final state interactions are calculable. Satz argued that one can subtract the uncalculable $\chi \rightarrow J/\psi + \gamma$ contribution by detecting the photon.

3. Disoriented Chiral Condensate?

Equilibrium high temperature QCD manifests a chiral symmetry if the light up and down quarks are taken to be massless. However, a phase transition occurs at a critical temperature $T_c \sim 140$ MeV at which chiral symmetry is broken by the formation of a scalar $\langle \bar{q}q \rangle$ condensate.

Rajagopal and Wilczek¹⁴ pointed out that the chiral condensate can be temporarily disoriented in the nonequilibrium environment of a heavy ion collision. Near T_c , the approximate chiral symmetry implies that the scalar condensate is nearly equivalent to a pion-like pseudoscalar isovector condensate $\sim \langle \bar{q}\gamma_5 \vec{\tau} q \rangle$, where $\vec{\tau}$ are the Pauli isospin matrices. Consequently, domains containing a macroscopic pion field can appear as the temperature drops below T_c . Such domains will eventually disappear as the system evolves towards the true vacuum in which only the scalar condensate is nonzero.

Bjorken, Kowalski, Taylor and others pointed out that DCCs can lead to fluctuations in the charged and neutral pion spectra.¹⁵ In the heavy ion system, the evolving DCC domains can radiate pions preferentially according to their isospin content. However, the ability of experimenters to identify DCCs amidst the background produced by conventional mechanisms critically depends on the domains' size and energy content.¹⁶ At this meeting, Kluger discussed efforts to calculate DCC formation using the linear sigma model. In this model, the pion field is coupled to a scalar σ field that characterizes the scalar condensate¹. The fields interact through the potential $V = \lambda(\vec{\pi}^2 + \sigma^2 - v^2)^2/4 - H\sigma$ that is intended to describe the behavior of QCD near T_c .

Many agree¹⁶⁻¹⁸ that the scale of the domain size is fixed by the inverse sigma mass $m_\sigma^{-1} \sim \{\lambda v^2\}^{-1/2}$. The question is, what is the value of m_σ in the high density system? Kluger, Cooper, Mottola and Paz studied the time evolution of the linear sigma model in a self consistent large N approximation, where N is the number of pions. Domains are small in this model, perhaps $\sim 1 - 3$ fm, because m_σ is large at T_c . Alternatively, Müller and I observed that if $m_\sigma(T_c) = 0$ (as would be the case if chiral restoration were strictly second order), domains would be much larger and, perhaps, observable.¹⁸

If seen in ion-ion collisions, DCC's can provide information about the equation

of state of hot QCD. Similarly, the detection of seismic waves on Jupiter may teach us about the EOS of metallic hydrogen. Both effects are fascinating but may prove very difficult to observe!

But what about QCD? The nature of the phase transition is unknown for realistic values of the u , d and s quark masses. The real transition is likely continuous, but with the large increase in the energy density mentioned earlier. The linear sigma model does not describe this increase. Nevertheless, QCD can exhibit large fluctuations in the transition region indicative of nearly critical behavior as described by the three-flavor sigma model.¹⁹ Schäfer and Shuryak suggest that an instanton liquid model may capture both of these features. Schäfer observed that the pion suffers strong interactions at high T as in the sigma model.²⁰ Shuryak argued that the instanton liquid model can also explain the large energy density change in QCD. Models like this may therefore provide a more realistic context for studying dynamical phenomena such as DCC's than the linear sigma model.

To summarize, there has been substantial progress in understanding the hard-core phenomenology of Au+Au at the AGS and S+Au at the SPS. The heavy ion experimental program is driving towards heavier projectiles and higher energies, with Pb+Pb at the SPS this fall and RHIC at $\sqrt{s} = 200$ AGeV in 1999. Fascinating phenomena are expected and their complicated backgrounds are coming to be understood. There is every reason to keep looking up!

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References

1. F. Karsch in *Lattice 93*, eds. T. Draper, *Nucl. Phys. (Proc. Supp.)* **B34** (1994), p. 63.
2. See, *e.g.*, *Quark Matter 93*, eds. E. Stenlund *et al.*, *Nucl. Phys.* **A566** (1994).
3. C. R. Chapman, *Nature* **370**, 245 (1994).
4. Duffy, T.S. *et al.*, *Science* **263**, 1590 (1994).
5. M. S. Marley, *Ap. J. Lett.*, **427**, L63 (1994); D.M. Hunten *et al.*, *Geophys. Res. Lett.*, **21**, 1095 (1994); J. Harrington *et al.*, *Nature* **368**, 525 (1994).
6. G. Bjoraker, T. Herter, S. Stolovy, G. Gull and B. Pirger, World Wide Web communications, <http://newproducts.jpl.nasa.gov/sl9/news24.html> (1994).
7. D. E. Kahana, D. Keane, Y. Pang, T. J. Schlagel and S. Wang, nucl-th/9405017.
8. H. Hammel, MIT/NASA HST; See *e.g.* <http://seds.lpl.arizona.edu/sl9/sl9.html>.
9. K.J. Eskola, K. Kajantie, P.V. Ruuskanen, *Phys. Lett.* **B332**, 191 (1994).
10. B. Müller and X.-N. Wang, *Phys. Rev. Lett.* **68** 2437, (1992).
11. H. Zirin, *Astrophysics of the Sun* (Cambridge U. Press, 1988).
12. E. Braaten *et al.*, *Phys. Lett.* **B333**, 548, (1994).
13. S. Gavin and M. Gyulassy, *Phys. Lett.* **B214**, 214, (1988).
14. K. Rajagopal and F. Wilczek, *Nucl. Phys.* **B404**, 577 (1993).
15. J.D. Bjorken, K.L. Kowalski and C.C. Taylor, SLAC-PUB-6109 (April 1993).
16. S. Gavin, A. Gocksch and R.D. Pisarski, *Phys. Rev. Lett.* **72**, 2143 (1994).
17. D. Boyanovsky, H.J. de Vega, R. Holman, PITT-94-01 (1994), hep-ph/9401308, F. Cooper, Y. Kluger, E. Mottola, J.P. Paz, LANL preprint (1994), hep-ph/9404357.
18. S. Gavin and B. Müller, *Phys. Lett.* **B329**, 486 (1994); S. Gavin, BNL-60637 (1994), hep-ph/9407368.

19. S. Gavin, A. Gocksch, R. D. Pisarski, *Phys. Rev.* **D49** 3079 (1994).
20. A. Gocksch, *Phys. Rev. Lett.* **67** 1701 (1991).